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RESEARCH MEMORANDUM

THE EFFECT OF A CHANGE IN AIRFOIL SECTION ON THE HINGE-MOMENT CHARACTERISTICS OF A HALF-DELTA TIP CONTROL WITH A 60° SWEEP ANGLE AT A MACH NUMBER OF 6.9

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
October 15, 1954

CONFIDENTIAL

Unclassified)

NASA Tech. Pub. Announcement #71

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THE EFFECT OF A CHANGE IN AIRFOIL SECTION ON THE HINGE-MOMENT CHARACTERISTICS OF A HALF-DELTA TIP CONTROL WITH A 60° SWEEP ANGLE AT A MACH NUMBER OF 6.9

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SUMMARY

A theoretical and experimental investigation has been made of the effect of a change in airfoil section on the hinge-moment characteristics of a half-delta tip control with a 60° sweep angle. The tests were made at a Mach number of 6.9 and a Reynolds number of 0.64×10^6, based on tip-control mean aerodynamic chord. The controls were investigated at angles of attack of 0° and 8° over a control-deflection range of -14° to 14° and at zero control deflection over an angle-of-attack range of -12° to 12°.

The results indicate that at hypersonic Mach numbers the airfoil sections of half-delta tip control surfaces can have large effects on their hinge-moment characteristics, and these effects can be adequately predicted by shock-expansion theory. Linear theory, because of its inherent limitations, is not generally applicable at these Mach numbers, and where agreement with experimental results is obtained, this agreement will generally be found to be fortuitous.

INTRODUCTION

An investigation has been undertaken in the Langley 11-inch hypersonic tunnel to determine the aerodynamic characteristics of several types of control surfaces. The results of tests at a Mach number of 6.9 on one of these control surfaces, a half-delta tip control on a 60° delta wing reported in reference 1, showed that results of linear theory and two-dimensional shock-expansion theory adequately predicted the experimental control-surface hinge-moment characteristics at small deflection angles. However, since linear theory considers only the plan-form effects

of an infinitely thin wing, the agreement of the results of linear theory with shock expansion and experimental results appeared to be fortuitous as a result of the particular airfoil section tested, as was pointed out in reference 1, and it was expected from theoretical considerations that a small change in the airfoil section of this tip control would produce a large change in its hinge-moment characteristics.

The purpose of the present paper is to show theoretically and to verify experimentally the effect of a change in airfoil section on the hinge-moment characteristics of a half-delta tip control of 60° sweep angle at a Mach number of 6.9 and a Reynolds number of 0.64×10^6 based on the tip-control mean aerodynamic chord.

SYMBOLS

M Mach number

R Reynolds number, based on tip-control mean aerodynamic chord

p static pressure

γ ratio of specific heats for air

q dynamic pressure, $\frac{\gamma}{2} M^2 p$

c control root chord

$\bar{c}$ control mean aerodynamic chord, $\frac{2}{3} c$

S control plan-form area

x distance from center of pressure to hinge line

H control hinge moment

C_h control hinge-moment coefficient, $\frac{H}{qS\bar{c}}$

α wing angle of attack

δ control deflection (positive when trailing edge is deflected downward)

θ flow deflection angle

ϕ airfoil surface angle with respect to chord line

$$C_{h_\delta} = \frac{\partial C_h}{\partial \delta} \text{ at } \delta = 0^\circ;\ \alpha = 0^\circ$$

$$C_{h_\alpha} = \frac{\partial C_h}{\partial \alpha} \text{ at } \alpha = 0^\circ;\ \delta = 0^\circ$$

Subscripts:

o refers to free-stream conditions

1 refers to foremost area of control plan form

2 refers to rear area of control plan form

DISCUSSION OF THEORY

Shock-Expansion Theory

At hypersonic Mach numbers, two-dimensional flow can occur over large portions of control surfaces (or wings) even when their aspect ratios are low because three-dimensional effects are confined to small regions within highly swept Mach cones. When this is the case, a good approximation to the flow quantities over the entire surface can be obtained by use of shock-expansion theory provided the angle of inclination for shock detachment is not exceeded. (See ref. 2.)

In the application of shock-expansion theory to a configuration with swept leading edges it must be pointed out that correct use of the theory requires that the flow quantities in the plane normal to the leading edge be considered. However, calculations have shown that for controls with thin airfoil sections and sweep angles as high as 70° at hypersonic Mach numbers, only a small error is introduced by considering the flow quantities in the streamwise direction. Thus, the results of shock-expansion theory presented in this report were computed by considering the flow quantities in the streamwise direction. Of course, in either method the determination of the limiting angle for shock detachment must be carried out in the plane normal to the leading edge.

By use of shock-expansion theory, some insight into the effect of airfoil section shape can be obtained by a consideration of the following expression for hinge-moment slope parameters $C_{h_{\alpha,\delta}}$ (meaning C_{h_α} or C_{h_δ}):

$$C_{h_{\alpha,\delta}} = -\frac{4}{\gamma M^2 S\bar{c}} \int_S x\left[\frac{\partial}{\partial\theta}\left(\frac{p}{p_o}\right)\right]_{\theta=\phi} dS \tag{1}$$

which has been derived in a manner analogous to that for the section lift-curve-slope parameter at $\alpha = 0^\circ$ in reference 3. In the preceding expression $C_{h_{\alpha,\delta}}$ is seen to be a function of the distribution over the control surface S of the quantity $x\left[\frac{\partial}{\partial\theta}(p/p_o)\right]_{\theta=\phi}$ where x is the distance between the local center of pressure and the hinge line and $\left[\frac{\partial}{\partial\theta}(p/p_o)\right]_{\theta=\phi}$ is the rate of change of the local to free-stream static-pressure ratio with surface inclination. Although the parameter $\left[\frac{\partial}{\partial\theta}(p/p_o)\right]_{\theta=\phi}$ is directly related to the airfoil section geometry, no simple conclusion as to the relation of $C_{h_{\alpha,\delta}}$ with airfoil section geometry can be made because of the multiplication factor x without referring to a specific control configuration. However, certain general conclusions can be made evident by a consideration of the variations of $\frac{\partial}{\partial\theta}(p/p_o)$ with θ for Mach numbers of 6.9 and 10 as shown in figure 1. At $M = 6.9$, $\frac{\partial}{\partial\theta}(p/p_o)$ is seen to vary considerably with θ indicating that changes in airfoil section can have a large effect on $C_{h_{\alpha,\delta}}$. Because of the greater slope of the curve for $M = 10$, a given change in airfoil section would cause a larger percentage change in $C_{h_{\alpha,\delta}}$. At lower Mach numbers the variation of $\frac{\partial}{\partial\theta}(p/p_o)$ with θ decreases so that, for tip controls over which a large portion of two-dimensional flow occurs, a smaller percentagewise effect of airfoil section on $C_{h_{\alpha,\delta}}$ is to be expected.

Effect of a Change in Airfoil Section

The effect of a change in airfoil section on the hinge-moment slope parameters of a half-delta tip control can be illustrated by the application of equation (1) to a control with a modified double-wedge and wedge airfoil section, both having the same included leading-edge wedge angle. To assist in this illustration, consider the plan form of the wedge control broken up into two areas equal to those of the modified double-wedge control as shown in figure 1. Since the leading-edge wedge angle of the controls considered is small, the entropy loss through the leading-edge shock may be neglected and equation (1) for either control then reduces to

$$C_{h_{\alpha,\delta}} = -\frac{4}{\gamma M^2}\left\{\frac{x_1}{\bar{c}}\frac{S_1}{S}\left[\frac{\partial}{\partial\theta}\left(\frac{p}{p_o}\right)\right]_{\theta=\phi_1} + \frac{x_2}{\bar{c}}\frac{S_2}{S}\left[\frac{\partial}{\partial\theta}\left(\frac{p}{p_o}\right)\right]_{\theta=\phi_2}\right\} \tag{2}$$

The first term is identical for either airfoil section and the second term differs only in the parameter $\frac{\partial}{\partial\theta}\left(\frac{p}{p_o}\right)$ which is a function of the rear surface angle ϕ_2. Thus, at high Mach numbers a positive increase in the rear surface angle of the modified double-wedge control will substantially increase $C_{h_{\alpha,\delta}}$.

Linear Theory

The results of three-dimensional linear theory as obtained from references 4 and 5 have been used to predict the experimental hinge-moment slope parameters C_{h_α} and C_{h_δ}, respectively. However, two-dimensional linear theory or its equivalent at small angles (shock-expansion theory applied to a flat plate) can be used as a good approximation to the three-dimensional linear theory provided two-dimensional flow exists over a large portion of the control surface. Under the assumptions of linear theory, the effect of thickness disappears except for drag calculations, and thus linear theory precludes any estimation of the effects of changes in airfoil sections on hinge-moment characteristics.

APPARATUS

Wind Tunnel

The tests were conducted in the Langley 11-inch hypersonic tunnel using a single-step two-dimensional nozzle which provided sufficiently uniform flow for model testing in the central core of the test section about 5 inches square in cross section. A description and calibration of this nozzle is given in reference 6.

Model

The principal dimensions of the semispan wing and the two interchangeable tip controls used in this investigation are shown in figure 2. The basic wing had a delta plan form with a leading-edge sweep angle of 60° and a corresponding aspect ratio of 2.31.

The wing panel exclusive of the control surface had a modified hexagonal or wedge-slab-wedge airfoil section 3-percent thick at the wing root with constant thickness outboard to the 55.7-percent-semispan station. The included leading-edge wedge angle, measured parallel to the air stream, was 5.7°. The trailing edge was blunt and had a constant thickness of 1.5 percent of the wing root chord.

The two tip controls had the same plan form, root chord, and hinge-line location, but differed in their airfoil sections. The control had a 60° half-delta plan form, the control root chord was located at the 55.7 percent wing semispan station, and the control hinge line was normal to the root chord and located at 60 percent of the control root chord. Both tip controls had the same included leading-edge wedge angle, 5.7°; however, one control had a modified double-wedge airfoil section with a blunt trailing edge of constant thickness, 1.5 percent wing root chord, extending to 65.1 percent of the control semispan and from there tapering to zero thickness at the control tip. The other control had a 9.97-percent-thick wedge airfoil section. The gap at the wing-control parting line was maintained at approximately 0.007 inch.

The semispan wing-tip control combinations were mounted vertically in the center of the test section by means of the support shown in figure 3. The support housed the electrical strain-gage balance used to measure hinge moments and was insulated with asbestos sheets to minimize heating effects.

The angle of attack and/or control deflection was set prior to each run. The angle of attack was varied by rotating the support to predetermined settings measured from the test-section side plate. The control defections were set by use of a series of wedge-shaped gage blocks, one for each of the control deflections tested.

TESTS

The tests were made at a stagnation pressure of 37 atmospheres and a stagnation temperature of about 675° F. This high stagnation temperature was used to avoid air liquefaction. Warpage of the thin slit-like minimum of the nozzle brought about by thermal stresses caused a slight variation of Mach number with time. Therefore, all data were recorded at a specific time corresponding to $M = 6.9$. These test conditions correspond to a Reynolds number of 0.64×10^6, based on tip-control mean aerodynamic chord. In order to eliminate water condensation effects, the absolute humidity was kept less than 1.87×10^{-5} pounds of water per pound of dry air.

The tests were made at angles of attack of 0° and 8° over a control deflection range from -14° to 14°, and at zero control deflection over an angle-of-attack range from -12° to 12°.

PRECISION OF DATA

From a consideration of the errors involved in measuring the pertinent quantities - Mach number, static pressure, and hinge moment - required to obtain the hinge-moment coefficients, the estimated maximum error in C_h was ± 0.001. The estimated error in α and δ was $\pm 0.15^\circ$.

DISCUSSION OF TEST RESULTS

Hinge Moments

The experimental results are presented in figure 4 as the variations of hinge-moment coefficient with control deflection at $\alpha = 0^\circ$ and $\alpha = 8^\circ$ for the modified double-wedge and wedge control sections. The variations of hinge-moment coefficient with angle of attack at zero control deflection for both controls is shown in figure 5. These figures show that the wedge airfoil section gave consistently greater values of C_h than the modified double-wedge airfoil as was indicated theoretically in a previous section. For comparison with experimental results the hinge-moment coefficients predicted by shock expansion and linear theories are included in figures 4 and 5. At $\alpha = 0^\circ$ (fig. 4) and $\delta = 0^\circ$ (fig. 5), the results of both shock expansion and linear theory show fairly good agreement with the experimental results of the tip control with the modified double-wedge airfoil section over the range of the investigation. However, linear theory completely underestimates whereas shock-expansion theory predicts adequately the experimental results of the tip control with the wedge airfoil section. At $\alpha = 8^\circ$ (fig. 4) and positive control deflections, the results of shock-expansion theory are again in fairly good agreement with the experimental results of the modified double-wedge configuration and in excellent agreement with those of the wedge configuration, but at negative control deflections shock-expansion theory fails to predict the experimental coefficients for both tip controls.

Shock-expansion theory indicates that for these controls at $\alpha = 8^\circ$ the maximum control deflection for shock attachment is $\delta = 10^\circ$. Although at higher control deflections the theory is not considered valid, the present data show good agreement with theory at $\delta = 14^\circ$, especially for the wedge airfoil. Additional data at higher control deflections would be required to determine whether this agreement is due to inaccuracies in

the data or compensating effects caused by the gap at the wing-tip-control parting line.

Slope Parameters

The hinge-moment slope parameters C_{h_δ} and C_{h_α} for both configurations at 0° control deflection and angle of attack, as measured from experimental results and predicted by linear and shock-expansion theories, are presented in the following table:

Airfoil section	Slope parameter	Experiment, per degree	Linear theory, per degree	Shock-expansion theory, per degree
	C_{h_δ}	-0.0010	-0.00102	-0.00083
	C_{h_α}	-0.0010	-0.00105	-0.00083
	C_{h_δ}	-0.0016	-0.00102	-0.00162
	C_{h_α}	-0.0019	-0.00105	-0.00162

The experimental results show that changing the airfoil section from a modified double wedge to a wedge increased the value of C_{h_δ} by 60 percent and C_{h_α} by 90 percent. By locating the hinge line in a more forward position than that used in this investigation, somewhat smaller percentage increases in C_{h_α} and C_{h_δ} would have been obtained. The theoretical results show that, although linear theory predicts accurately the experimental results of the modified double wedge, it completely underestimates those of the wedge. Shock-expansion theory, however, gives adequate predictions of the experimental results for both tip controls.

It must be emphasized that the close agreement occurring between the experimental results of the modified double-wedge control and the predictions of linear theory is fortuitous. By means of the shock-expansion-theory solution for a flat plate as an approximation to linear theory, this fact can be established by referring again to figure 1 and noting that, at $M = 6.9$, the value of $\frac{\partial}{\partial\theta}\left(\frac{p}{p_o}\right)$ indicated for the flat plate at $\theta = 0^\circ$ is intermediary to the values of $\frac{\partial}{\partial\theta}\left(\frac{p}{p_o}\right)$ indicated for the two portions of the modified double-wedge control with surface angles $\theta_1 = 2.85^\circ$ and $\theta_2 = -3.20^\circ$. Thus, compensating effects are present which result in a value of $C_{h_{\alpha,\delta}}$ for this control which is in close agreement with that predicted by linear theory.

CONCLUSIONS

The effect of a change in airfoil section on the hinge-moment characteristics of half-delta tip controls on a 60° delta wing has been investigated in the Langley 11-inch hypersonic tunnel at a Mach number of 6.9. The results of this investigation lead to the following conclusions.

1. At hypersonic Mach numbers the airfoil sections of half-delta tip-control surfaces have a large effect on their hinge-moment characteristics and these effects can be adequately predicted by shock-expansion theory.

2. Linear theory, because of its inherent limitations, is not generally applicable at these Mach numbers and where agreement with experimental results is obtained, this agreement will generally be fortuitous.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 3, 1954.

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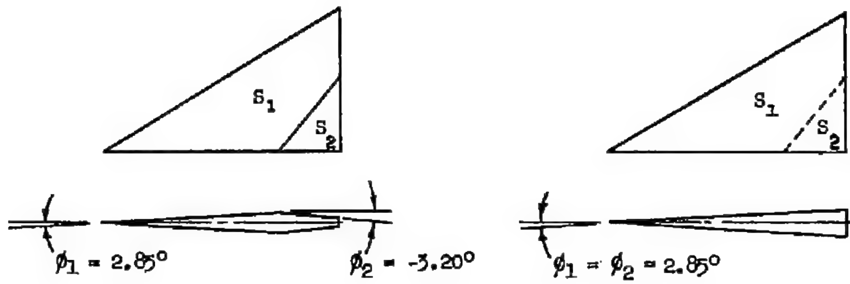

Tip controls referred to in "Discussion of Theory"

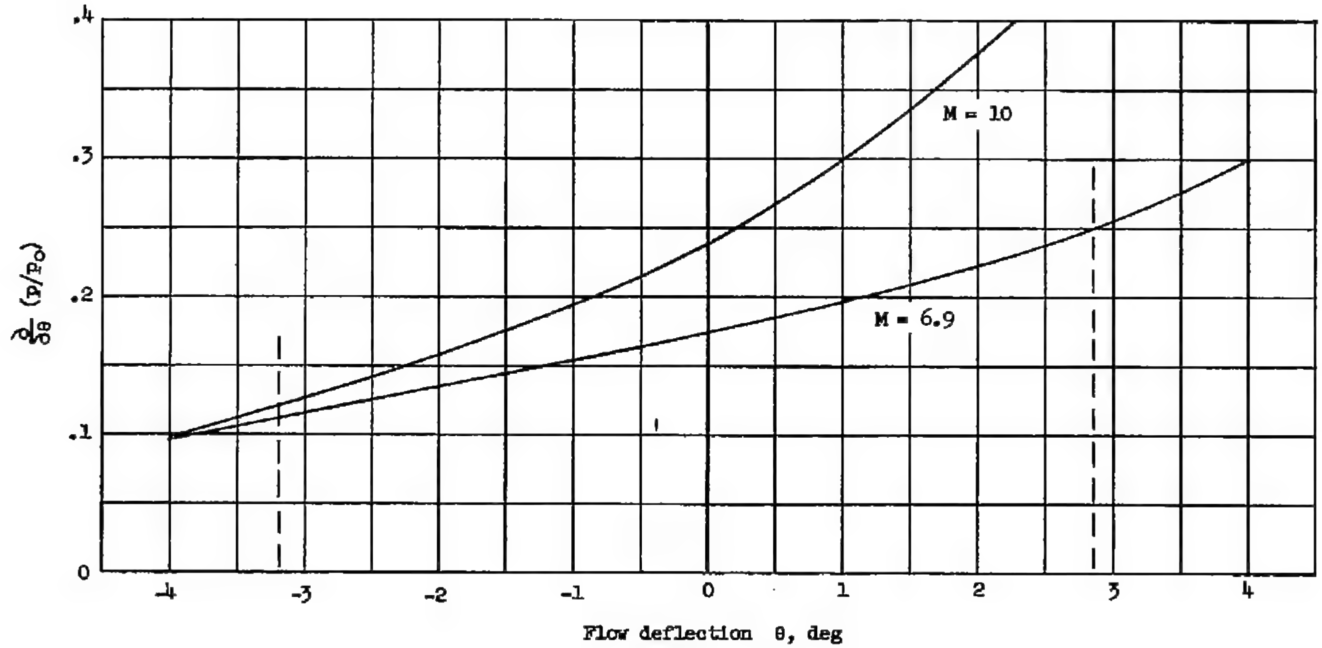

Figure 1.- The variation of $\frac{\partial}{\partial\theta}(p/p_o)$ with flow deflection θ at Mach numbers of 6.9 and 10.

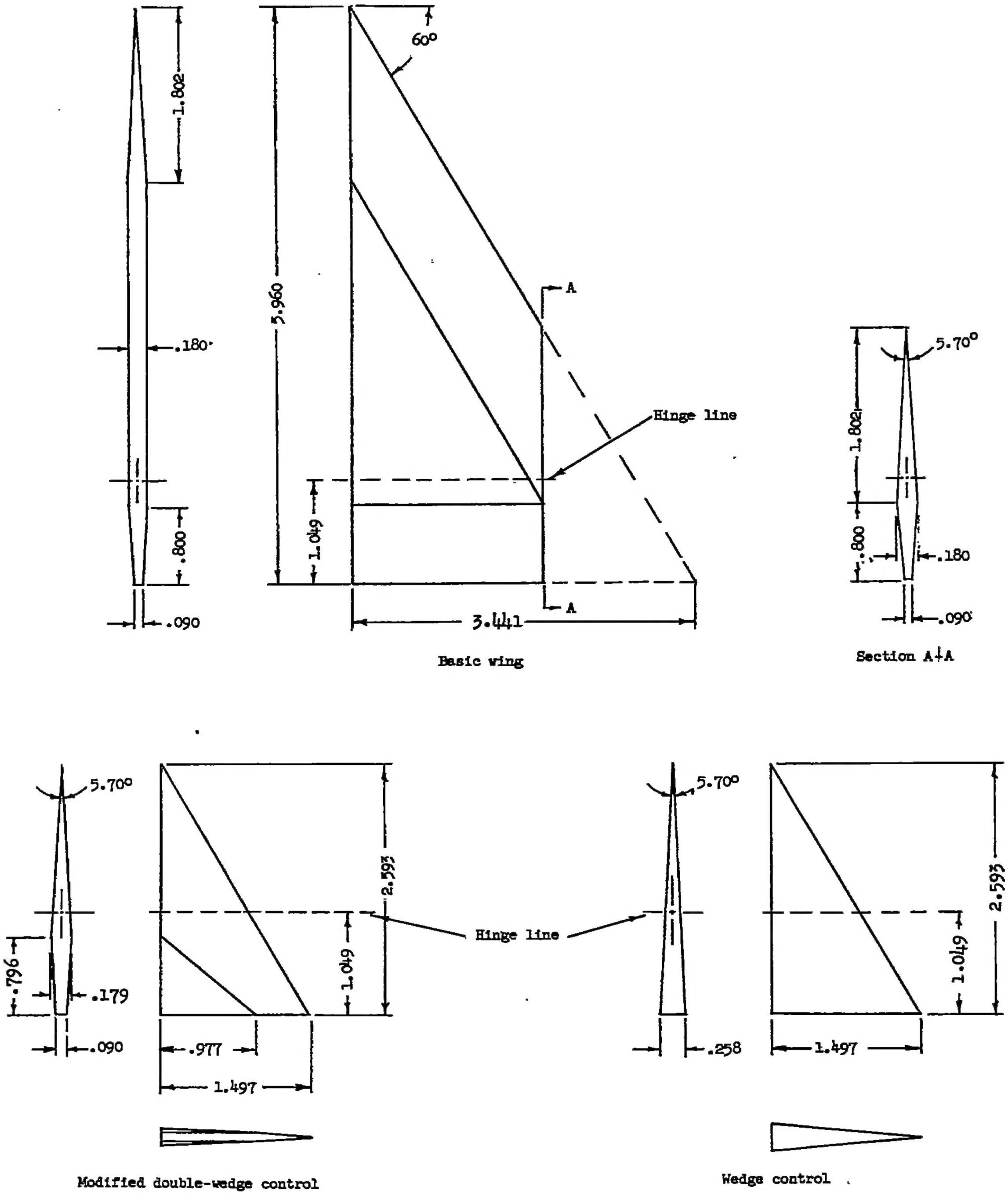

Figure 2.- Sketch of basic wing and tip-control configurations. All dimensions in inches.

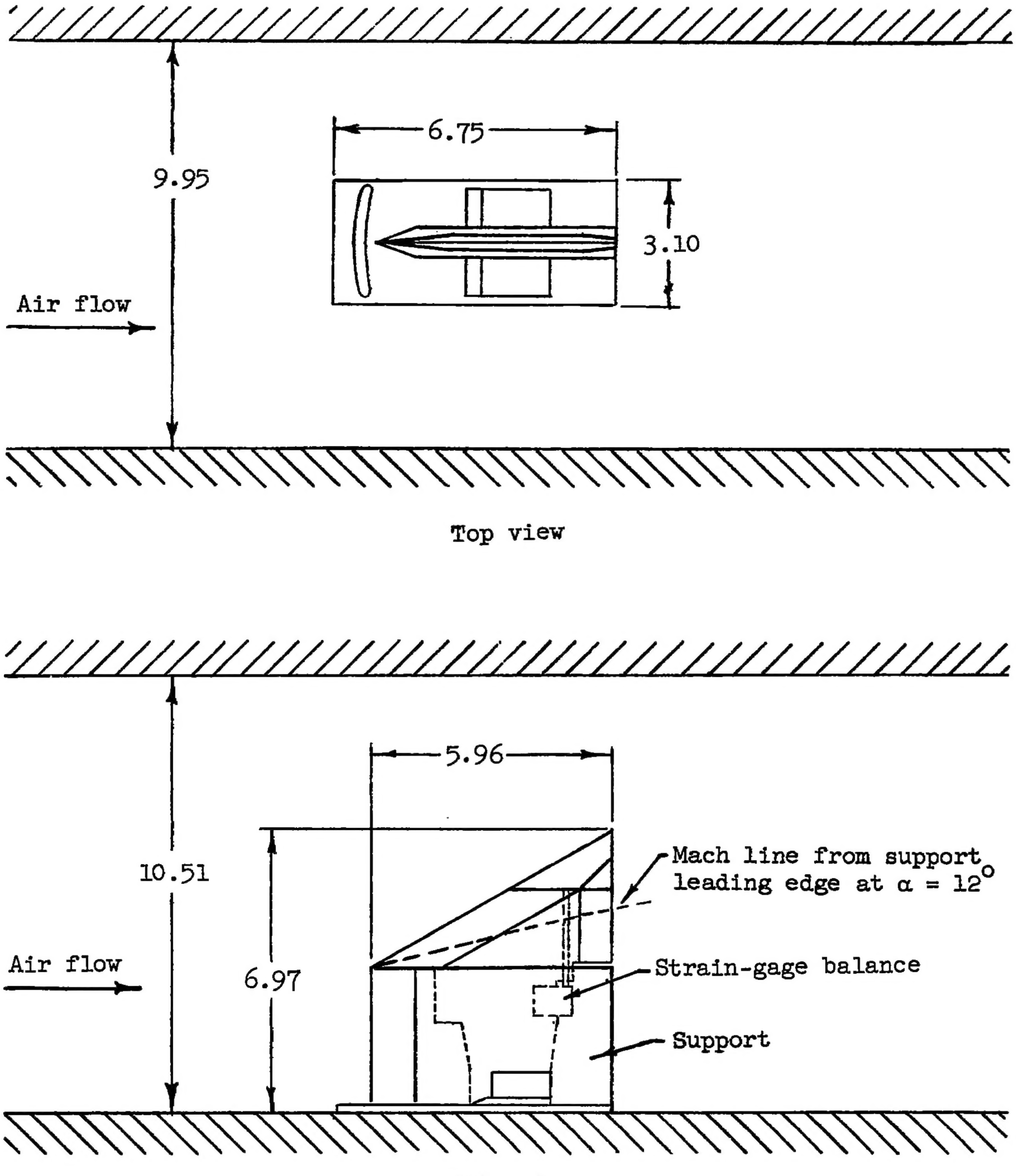

Figure 3.- Schematic diagram of the test section of the Langley 11-inch hypersonic tunnel and model arrangement. All dimensions in inches.

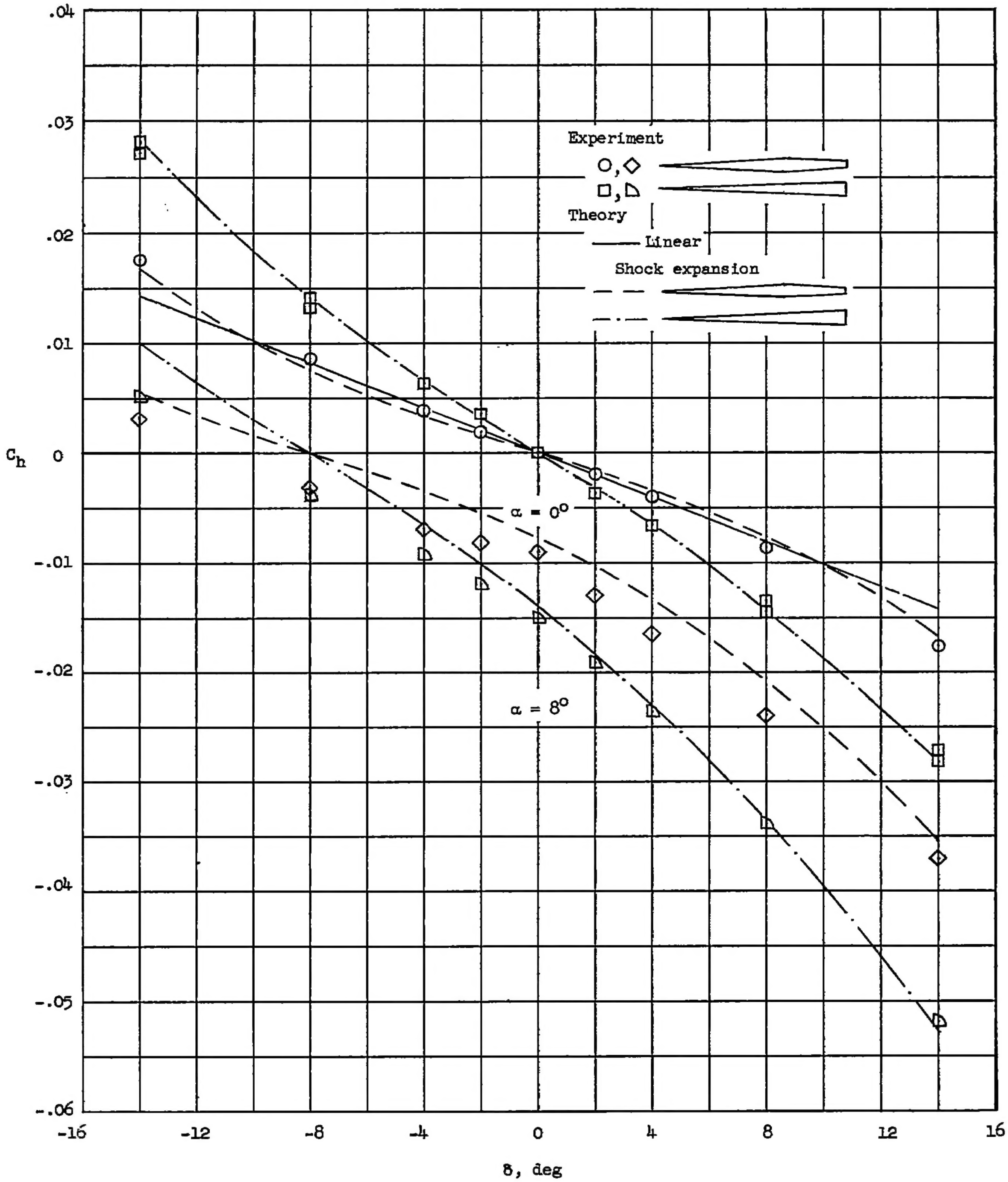

Figure 4.- The variation of control-surface hinge-moment coefficient with control deflection for two 60° sweptback half-delta tip controls with a modified double-wedge and wedge airfoil sections. M = 6.9; $R = 0.64 \times 10^6$.

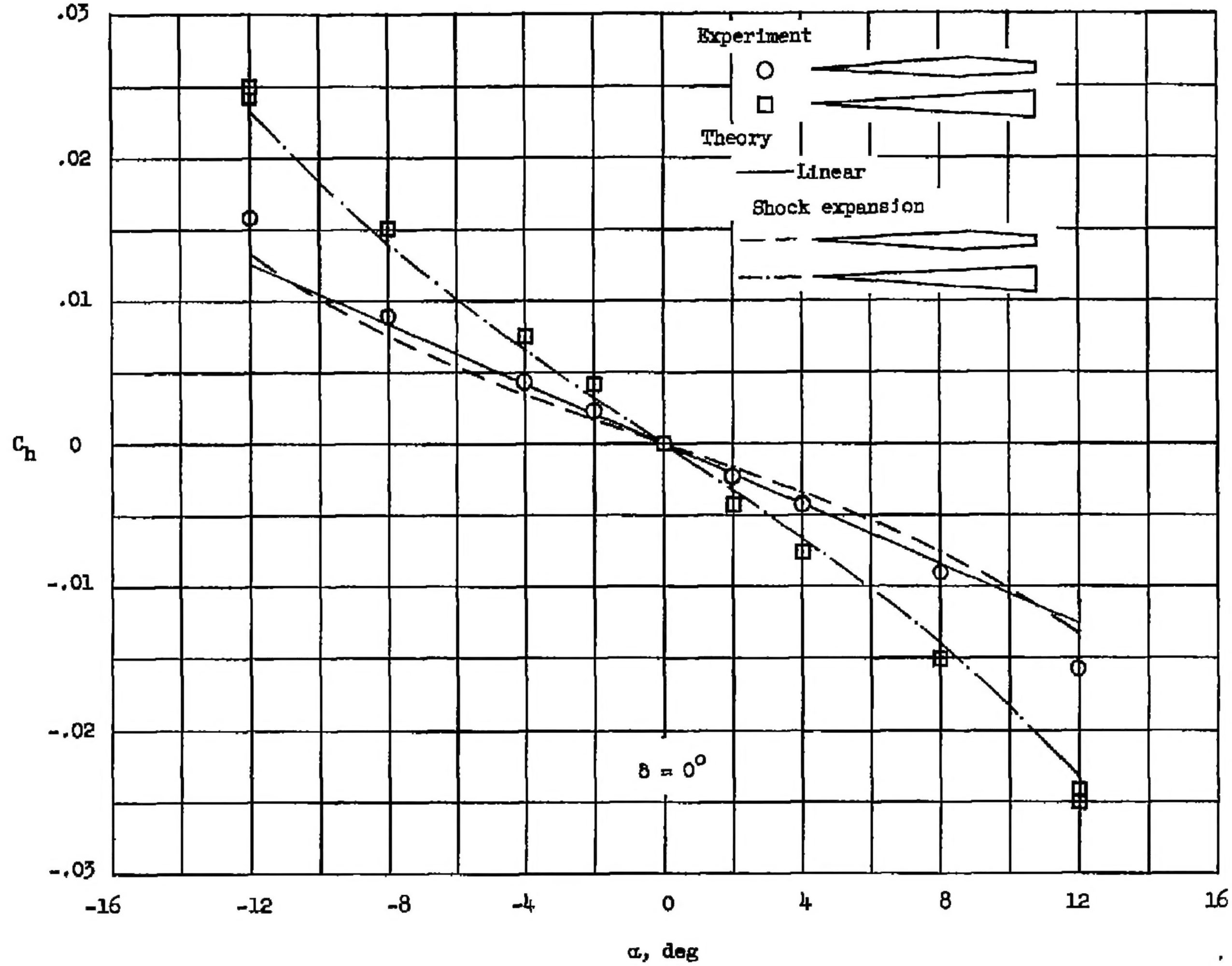

Figure 5.- The variation of control-surface hinge-moment coefficient with angle of attack for two 60° sweptback half-delta tip controls with a modified double-wedge and wedge airfoil sections. $M = 6.9$; $R = 0.64 \times 10^{6}$.